ESTCP
Cost and Performance Report

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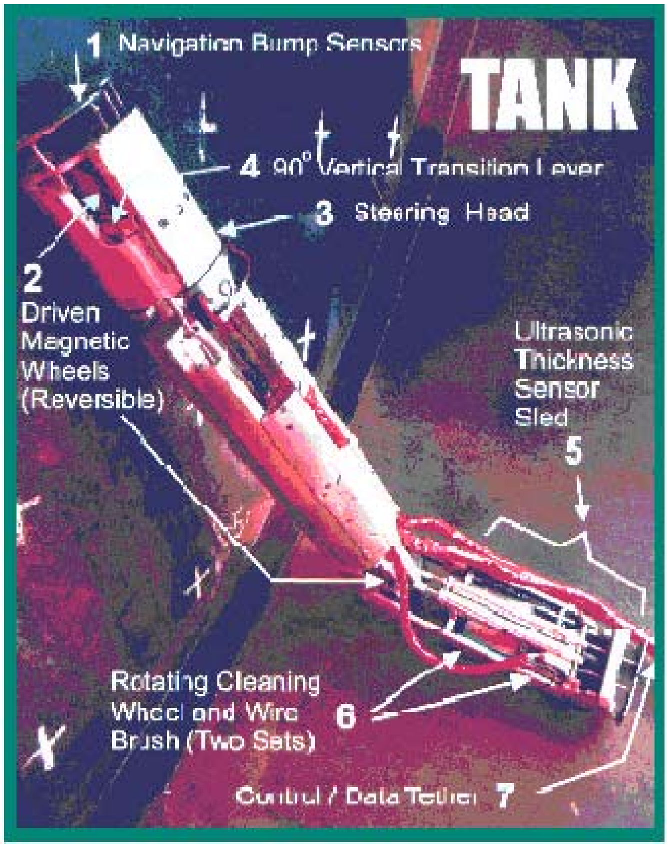

Fury: Robotic In-Situ Inspection/Condition Assessment System for Underground Storage Tanks

August 1999

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

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LIST OF ACRONYMS

AAF	Army Airfield
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
CERL	Construction Engineering Research Laboratories
CRADA	Cooperative Research and Development Agreement
EMAT	Electromagnetic Acoustic Transducer
ESTCP	Environmental Security Technology Certification Program
MLE	Maximum Likelihood Estimate
NDT	Non-Destructive Testing
NLPA	National Leak Prevention Association
O&M	Operating and Maintenance
PPE	Personal Protective Equipment
SBIR	Small Business Innovative Research
TRADOC	United States Army Training and Indoctrination Command
USACERL	United States Army Construction Engineering Research Laboratories
UST	Underground Storage Tank

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ACKNOWLEDGMENTS

Fury was developed by the U.S. Army Construction Engineering Research Laboratory (USACERL) in conjunction with RedZone Robotics, Inc., Pittsburgh, PA. Funding for the effort by the Small Business Innovative Research Program (SBIR) and the Army Petroleum Center, in addition to the Environmental Security Technology Certification Program (ESTCP) is gratefully acknowledged. Outstanding personal efforts by Mr. Jeff Timmins, Mr. Robert Weber (USACERL), Mr. Troy Lehman (RedZone) and especially Mr. Tim Richardson (Fort Lee, VA) are also acknowledged.

Points of contact can be found in Appendix A.

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1.0 EXECUTIVE SUMMARY

The Code of Federal Regulations (40 CFR 280-281) required all underground storage tanks (USTs) containing petroleum products to be brought into compliance to prevent environmental contamination through leakage. Replacing all older USTs can, in some cases, be prohibitively expensive. One alternative to requiring that tanks pass a precision tightness test is to retrofit USTs with cathodic protection for continued use. To pursue this alternative, there is a need for more cost-effective and reliable tank condition assessment methods.

The U.S. Army Construction Engineering Research Laboratories (USACERL) in conjunction with RedZone Robotics, Inc. of Pittsburgh, PA developed a remote, robotic UST condition inspection/assessment system named *Fury* to meet this need. *Fury* is a robotic crawler, which moves inside a UST by means of magnetic wheels. It includes 90-degree transition arms for robot positioning on tank end-caps and has a central pivot to allow for full motion of the steering head. The robot is designed to fit through an existing small diameter pipe, which mitigates invasive tank entry during assessment and allows for non-destructive evaluation. Control of the *Fury* is accomplished through a tether attached to the rear of the robot. *Fury* utilizes ultrasonic transducers on a sensor sled to obtain approximately 90,000 wall thickness measurements per hour at over 95% of cylindrical-wall or end-cap locations.

Under this Environmental Security Technology Certification Program (ESTCP) project, *Fury* was (1) successfully validated on a subsequently excavated UST at Fort Lee, VA from 18-26 August, 1996, and (2) successfully demonstrated in three USTs at Hunter Army Air Field (a sub-unit of Fort Stewart, GA) from 18 February to 7 March, 1997. *Fury* provided faster inspections and more reliable data, identified the most severely pitted wall regions, and avoided the expense and safety issues associated with confined space entry, which is required for conventional manual inspection methods. *Fury* inspection of a typical 30-50,000 gallon UST took less than one day. *Fury* is ultimately intended for deployment in tanks containing fuel while the headspace is filled with a protective blanket of inert gas, which avoids interruption of normal operations. Safety certification for this duty is presently being sought. Cost estimates for a *Fury* inspection system showed a payback of less than 2.5 years, and a per-tank assessment cost between $600-$1,200, which was $2,000-$4,000 per tank less than the estimate for conventional manual invasive methods.

The results of *Fury* condition assessments can be used to make better informed management decisions concerning upgrade versus replacement. A significant cost could be avoided for each tank found suitable for upgrade. Potential cost savings from avoiding the replacement of only 10% of the nationwide UST inventory are as high as $10 billion. *Fury* can also be used for ongoing UST condition assessment, assessment of aboveground tanks, and underwater applications such as inspection of submerged sheet-piling.

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2.0 TECHNOLOGY DESCRIPTION

2.1 BACKGROUND TECHNOLOGY DEVELOPMENT

The Environmental Protection Agency (EPA) regulates underground storage tanks (USTs) containing petroleum products, which are a potential source of soil and ground water pollution, in the Code of Federal Regulations (CFR). All existing UST systems were required to be, or upgraded to be in compliance with one of the alternatives allowed in 40 CFR 280-281 by no later than December 22, 1998 **[1]**. These alternatives include upgrading with cathodic protection, total UST replacement, internal lining (which is banned by Army Regulation 200-1, however) or closure. The integrity of USTs that were 10 or more years old needs to be ensured prior to upgrade.

The U.S. Army owns and operates some 20,000 USTs that must meet the compliance requirements of 40 CFR 280-281. One cost-effective, compliance option for USTs over 10 years old was condition assessment followed by upgrading with cathodic protection. In support of this option Army-wide, an improved robotic inspection and assessment technology was developed. The U.S. Army Construction Engineering Research Laboratories (USACERL) in conjunction with RedZone Robotics developed an automatic, ultrasonic *in-situ* tank assessment system, named *Fury*, which eliminates the problems of safety and expense often associated with tank inspection. The robot was developed through a Small Business Innovative Research (SBIR) Phase II contract, and was designed for implementation by DoD users, as well as by the commercial sector, in USTs containing hazardous petroleum products. The ultrasonic transducer was independently validated for use in the *Fury* system by the Naval Facilities Engineering Service Center.

The *Fury* robotic tank inspection system combines and extends two existing technologies to produce a cost-effective tool for UST inspection. Mobile robots have been used to move inspection devices over structures, and ultrasonic transducers have been extensively used to inspect metallic structures. *Fury* enters the tank through an existing fill pipe and moves over the interior surfaces of the tank to make ultrasonic time-of-flight measurements of wall thickness. When safety certified, *Fury* will be able to operate in tanks containing combustible liquids or vapors.

Ultrasonic thickness inspection methods are widely used in a number of industries. The American Society For Testing and Materials (ASTM) developed standards for measurement procedures **[2, 3]** as well as existing certification programs for technicians. Currently approved in National Leak Prevention Association (NLPA) 631, "Entry, Cleaning, Interior Inspection, Repair and Lining of Underground Storage Tanks" **[4]**, are hand-held ultrasonic thickness measurement techniques for the assessment of UST condition. It is expected that a *Fury* tank inspection covering 15% of the internal surface area of a tank as required by ASTM ES 40-94 **[5]** can be completed in less than eight hours from arrival to departure.

The predominant mode of UST failure is a result of external pitting, which is a localized form of corrosion that can lead to perforations. Seam or weld leaks are rarely the cause of failure. Pitting depends on several soil factors (e.g., soil resistivity, moisture, pH, temperature, chloride/sulfide levels), and subsequent perforation of the tank wall is directly correlated to pit depth. A typical UST will in time exhibit a distribution of pitting areas over the external surface that is exposed to soil, as well as a distribution of growing pit depths. With the addition of cathodic protection and the required follow-up system maintenance, all external UST corrosion can be stopped.

This ESTCP project served to: (1) validate the capabilities of *Fury* on a UST at Fort Lee, VA, in part through comparison with results from a third party inspection made after its subsequent excavation, and (2) demonstrate *Fury* on USTs at Hunter Army Air Field, located at Fort Stewart, GA.

2.2 TECHNOLOGY DESCRIPTION

The *Fury* robotic tank inspection system (shown in Figure 1) consists of four assemblies: the robot assembly, the inspection assembly, the tether management assembly and the operator console. The robot is designed to fit through an existing riser (4-inch diameter minimum), which mitigates invasive tank entry during assessment and allows for non-destructive evaluation.

The robot assembly supports and moves the inspection assembly over the tank interior surfaces. Permanent magnet wheels are used to attach the system to the tank walls allowing the system to move over the tank end-caps and overhead portions of the tank wall. Electric motors that power the robot components, are contained in the purged and pressurized lightweight aluminum robot housing. Steering and transition mechanisms provide robot mobility. The weight of the robot is approximately 5 lbs.

The inspection assembly contains the ultrasonic transducer used to measure wall thickness as well as the tank wall cleaning components. Tank wall cleaning is needed to assure ultrasonic wall thickness measurement performance at all locations. Powered cleaning wheels and brushes are used. The drive for the cleaning system is supplied by the robot assembly. The ultrasonic transducer is mounted in a guide shoe that protects the transducer and holds it perpendicular to and against the tank wall. The guide shoe directs couplant flow to the transducer/wall interface. Liquids contained in the tank are used for couplant to avoid contamination. All parts are grounded to the tank through the tether.

The tether management assembly drives the tether into or out of the tank and stores unused tether. A guide is provided to minimize tether damage. The tether management assembly is controlled from the operator console allowing one person operation. A couplant supply and a purge gas supply are contained in the tether management assembly. The operator console consists of an intelligent controller, an ultrasonic data acquisition system and power distribution unit. The operator console displays numeric and graphical information showing the position of the robot in the tank and robot status. It also controls the ultrasonic data acquisition system. The power distribution unit supplies electrical power to the intelligent controller, ultrasonic data acquisition system, robot assembly and the tether management assembly.

The robotic inspection system can be operated by a single trained technician. In addition to specific training to operate the robotic system, certification as a level IIR Non-Destructive Testing (NDT) technician is required to operate the ultrasonic system. The robotic inspection system equipment can be positioned at the tank site by the same operator assuming the tank site is vehicle-accessible. Any necessary removal of fill connectors and drop tubes can also be accomplished by the operator.

The robotic inspection system is assembled from a combination of off-the-shelf and custom components, and uses no proprietary technologies. Those custom components, such as robot housings, magnetic wheels and ultrasonic transducers, can be produced by a variety of sources. No exotic materials or manufacturing processes are used.

FURY

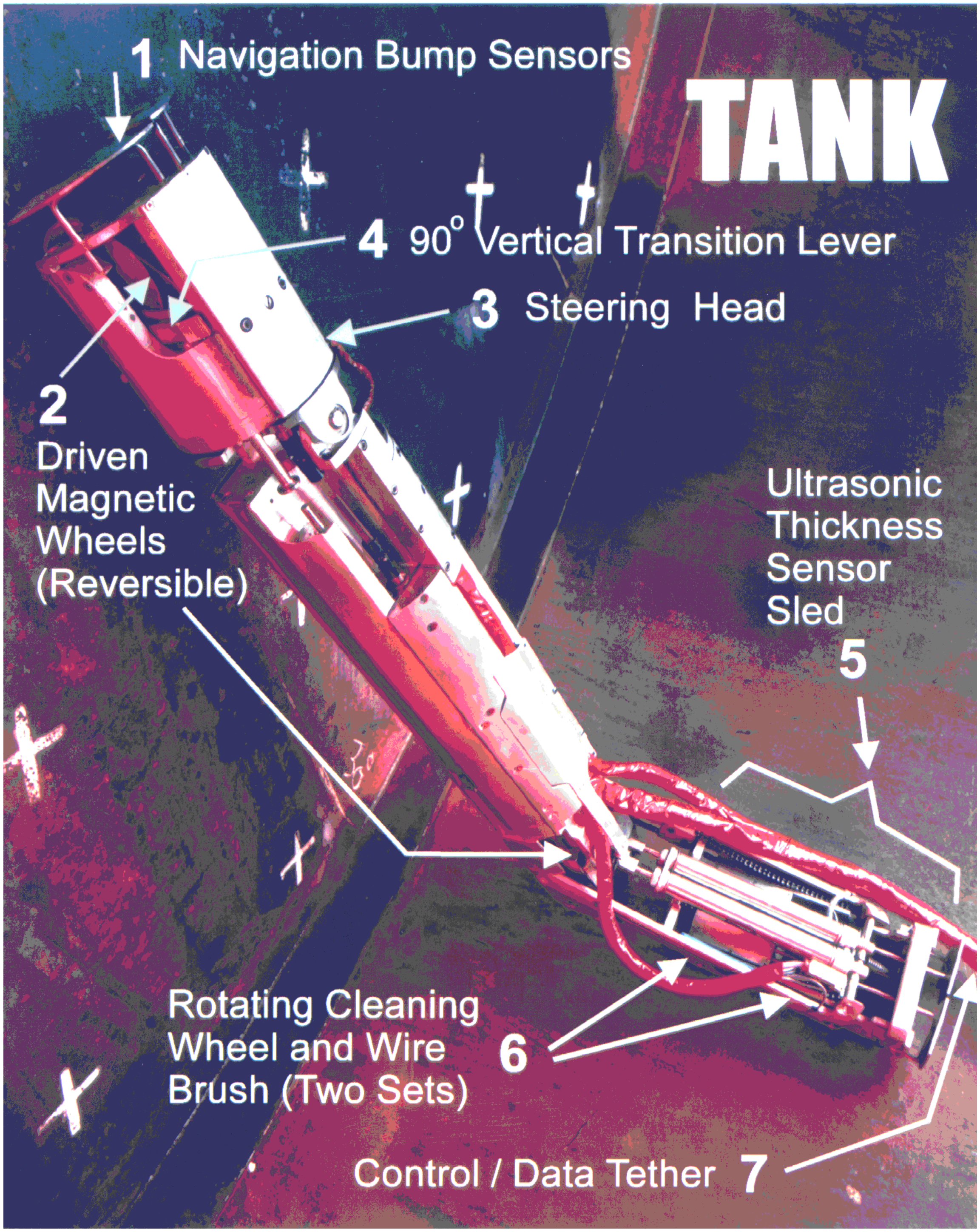

Figure 1. Photograph of F*ury* Robotic System

Internal inspection system components are designed to last the life of the product. Non-moving components are projected to last a minimum of 10 years while moving parts will likely require yearly inspection and possible replacement. Periodic replacement of the tether will be required as a result of abrasion and wear of the tether jacket. The tether is expected to last six months to one year depending on usage and test conditions. The high-pressure purge gas supply cylinder will require more frequent replacement. Generally, as the system is fielded, incremental improvements in durability will be made. The tether can be easily disconnected from the operator console so that inspection operations can continue by swapping assemblies. Normal vehicular maintenance will be required for the tow vehicle and trailer used to transport the robotic inspection system. No reliability problems are expected.

Safety approval or certification for submersed operation in fuel is being sought for the robotic system. For these ESTCP demonstrations in de-fueled tanks, safety certification was not needed. The lessons learned from the demonstration field experience will be incorporated into a redesigned system, which can obtain safety approval. The considerable advantage of certification would be to allow *Fury*'s use in tanks containing fuel. Tanks would not have to be emptied, cleaned, purged, or made inert prior to inspection. This eliminates the risk of spillage during emptying and cleaning, and the disposal of tank residuals and cleaning materials. Disruption of tank operation is also eliminated and the tank can remain in service during the inspection. Future systems will include a tether handling system to prevent any loss of tank contents.

2.3 FACTORS AFFECTING TECHNOLOGY PERFORMANCE

Robot mobility may be reduced by the presence of obstacles in the tank such as tank reinforcements, particularly reinforcements of tank end-caps, and loose objects in the tank. Robot mobility and ultrasonic performance may be affected by very firm sludge that cannot be displaced by the robotic system. Internal corrosion is not expected to affect performance. The amount of oxygen necessary for corrosion in contact with the internal tank walls is limited by the presence of fuel during regular fuel-storage duty. Correction for any existing internal coating that could affect the thickness measurement, is required during data analysis. The various media in contact with the outside of an UST should have no effect on ultrasonic thickness measurements.

2.4 ADVANTAGES COMPARED TO CONVENTIONAL TECHNOLOGIES

The robot assembly, inspection assembly and tether are small enough to enter the underground storage tank through the 4-inch diameter pipe used to fill the tank. This eliminates the need to dig through pavement and earth to reach the tank and cut an access opening in the tank. The compact size of the unit avoids damage to the tank or piping that would be caused by digging and reduces disruption at the tank site. Since the robotic inspection system is operated remotely and does not require workers to enter the tank, confined space exposure is eliminated and chemical exposure is reduced. The robot assembly can also move the inspection assembly over 95% of the accessible interior of the tank.

Human invasive inspection is the conventional technology that has been used for many years to determine tank condition. Personnel enter the tank to prepare it for inspection and to perform the inspection. The procedure consists of emptying, purging/inerting, unearthing, cutting, entering, desludging, grit blasting, vacuuming, visual and manual inspection (including ultrasonics, probing, hammer testing, etc.), and restoring the site after inspection. Internal manual inspection is required before tank lining, but is not necessary before installing cathodic protection. This inspection method is described in API 1631 and included in 40

CFR '280.21 (b)(2)(I) **[1]**.

More recently, video inspection and mean-time-to-corrosion-failure methods have been developed. Invasive video inspection methods insert specialized cameras and lighting into the fill tube of a UST. The camera, on the end of a long stick, is rotated, raised, and lowered to provide a full view of the tank interior. High-magnification lenses and explosion-proof lights are used. The tank must be emptied prior to inspection. Sludge removal and cleaning may be required to expose the tank wall for inspection.

The advantages of video inspection include creation of a visual record of the tank interior. Disadvantages include separate sludge removal costs, no surface cleaning, and surface-only characterization. Video inspection is somewhat disruptive in that the equipment, truck, and personnel are stationed over the tank pad. Another disadvantage is that it is a proprietary service.

Mean-time-to-corrosion-failure is a predictive method, based upon soil characteristics and tank age, that has been approved by many states for testing prior to cathodic upgrade. Tank site soil samples are laboratory tested for parameters known to promote tank corrosion including soil pH, resistivity, sulfides, moisture, and tank size. Parameter values are input into a mathematical model, which calculates likelihood of corrosion failure for tanks of a given age at the site.

The advantages of mean-time-to-corrosion-failure inspection include no disruption of tank operations. However, to date, the accuracy and value of the method to owner/operators remains unclear. Mean-time-to-corrosion-failure inspection is described in ASTM ES 40-94 **[5]**.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The major objective of this effort was to validate and demonstrate that the *Fury* system could maneuver throughout a UST and perform ultrasonic thickness measurements at a high sampling rate and provide reliable data that could be used to determine the condition of the tank. The following parameters were to be quantified and documented:

1. Main system components and associated equipment lists.

2. Set up time, procedures, and any unexpected impediments to inspection/assessment.

3. Actual inspection rate, which was required to be faster than conventional methods, and all procedures associated with UST integrity assessment including duration of each procedure.

4. Exit procedures (including data storage) and site clean up.

5. The data collected by this technology were to be used to help determine the suitability of tanks for upgrading with cathodic protection, thus avoiding the significant expense of replacement.

In accordance with both ASTM ES 40-94 **[5]** and NLPA 631 **[24]**, a tank is acceptable for upgrade with cathodic protection when 98% of the surface area has no pitting greater than 50% of the original wall thickness, and, for every m^2 of surface, the average wall thickness remaining is greater than 85% of the original wall thickness.

3.2 PHYSICAL SETUP AND OPERATION

The USTs tested during the demonstrations had been used for storage of fuel hydrocarbons, and had been emptied prior to the demonstrations. Thus, no process wastes were produced. The drop tube (if installed) had to be removed from the tank filler pipe. Drop tubes are thought to be present on about 15% of all USTs presently installed. During the demonstrations, personnel used level C personal protective equipment (PPE).

The first demonstration was conducted from 18-26 August, 1996 at Fort Lee, VA, where a tank that was scheduled for removal was used mainly for validation purposes prior to its excavation. In addition to a *Fury* inspection in accordance with ASTM ES40-94 **[5]**, a number of performance capabilities were documented on videotape using a real-time video feed from inside the tank to an outside monitor. The capabilities documented included: entry/exit through a riser pipe, adherence to the inner tank wall in all orientations, movement in the forward and reverse directions, obstacle sensing and avoidance, traversal of lap joints, transitions to and from end-cap walls, navigational accuracy, surface cleaning and ultrasonic thickness measurements. After the tank was removed, a third party inspection was performed by Midwest Research Institute (MRI), Inc. in accordance with procedures developed by the EPA during a study of available UST assessment methods **[6]**.

One of the most critical comparisons was that of the *Fury in-situ* ultrasonic thickness measurements to other reference methods. Three 5x5 square grids with 10 cm. spacing were utilized; one was located near the center bottom, one was approximately one half the distance to the end cap near the bottom, and one was on one end cap. These test grids were marked out with wax pencil and stamp markers. Each measurement location was circled using a vibrating engraver and a robot template positioner. The template was used to assure that *in-situ* comparison measurements with a hand-held ultrasonic thickness gauge were taken from exactly the same position. Both the robot sensor and the hand held thickness gauge were calibrated on the same step block before and after each group of measurements. After the tank was pulled, the grids were cut out of the tank, sectioned, and the same measurements were performed using a standard mechanical micrometer capable of an accuracy of 1/1000 of an inch.

The second demonstration was conducted at the Hunter Army Air Field (a sub-installation of Ft. Stewart, GA) from February 18 to March 7, 1997. *Fury* performed the remote, *in-situ* assessment of the condition of three 50,000 gallon USTs (from a total of thirty-one 50,000 gal. USTs at the site) according to ASTM ES40-94 **[5]**. These tanks were thought to be in good condition based on the condition of some previously removed tanks. Each of the tanks was selected from three separate pump stations, each consisting of a bank of 10 tanks. Emphasis was on measurements on the bottom one-third of the tank (the most susceptible to pitting) in order to provide a conservative assessment.

A checklist was completed prior to robot insertion into the tank. In the event of robot assembly failure, the robot could be retrieved by pulling on the tether. The geometry of standard cylindrical USTs is such that no tether binding or 90-degree bends were expected. Ultrasonic performance was controlled by calibrating the ultrasonic system on a calibration plate of known thickness before the robot was inserted into the tank, and by repeating the ultrasonic calibration after the robot was removed from the tank. Ultrasonic signals were displayed during inspection for review by the operator. Good practice also called for a check of calibration at the completion of the daily measurement activities or when the operator changed.

The nature of UST failure, predominantly manifested by exterior pitting corrosion, allows for accurate measurement using ultrasonic techniques. The ultrasonic system directly measures the remaining wall thickness of the tank. As specified in ASTM ES 40-94 **[5]**, wall thickness was measured to an accuracy of +/- 0.010 in. over the tank wall surface and in 0.125 in. diameter flat-bottom pits.

The nature of pitting corrosion is such that 100% inspection is not required to assess a buried structure's condition. The empirical relationship between the average pit depth (P) to the maximum pit depth has been found to be:

$$P(max) = 1.41\ P(avg.)$$

The sample size that was required for ultrasonic wall thickness measurements has been estimated (using extreme-value statistics) as 7% of the total wall area, according to an EPA report on inspection procedures and equipment **[7]**. In ASTM ES 40-94 **[5]**, this sample size was essentially doubled to 15% for increased environmental safety. Currently, a random sampling of the tank walls with no overlap is required, although some areas have been suggested where corrosion might occur more frequently (such as the bottom external third of the UST, the internal "water" line, and at the internal top subject to moisture condensation).

3.3 MONITORING PROCEDURES

For the Fort Lee tank, two hand-held reference methods were used by MRI for comparison with *Fury*: hand-held manual ultrasonic measurement (ASTM E114 **[2]** and E797 **[3]**) and micrometer based thickness measurement (ASTM G46-94) of UST sections cut after excavation. Two on-site audits were conducted at Fort Lee to verify that calibration and operating procedures were being followed, and that inspection data was being properly stored. One audit was conducted during *Fury* inspection, a second audit was performed while the manual tank-wall-thickness measurements were being made.

At Hunter AAF, the sampling plan for the three 50,000 gallon USTs required collection of ultrasonic thickness measurements on a minimum of 15% of the internal area from each tank. The sampling locations were distributed randomly over the tank walls and end caps.

Measurements were distributed as bands of thickness measurements over the tank surfaces. A band of continuous ultrasonic thickness data was taken during each traverse of the tank wall from end-cap to end-cap. To avoid overlap, each traverse was separated by a minimum of one band width. On the end-caps the traverses were from outer edge to outer edge, which necessarily resulted in some overlap near the center of the end-caps. Typically 20% over sampling was employed, depending on tank size. In total, a minimum of 15% of the inner tank surface was inspected with no overlap. A quantitative sense of position sensing/representation capabilities was also obtained.

Post inspection data analysis included the determination of an overall mean value (with end-caps and tank wall treated separately) as well as the distribution of the thinnest measurements. In addition, two life prediction algorithms were applied using soil data collected in accordance with ASTM ES40-94 **[5]** (see section 4.4 for statistical interpretation of results).

Several soil parameter measurements were taken by Russell Corrosion Consultants, Inc. (RCC) in association with Bushman & Associates, Inc. to assess external corrosion and determine the suitability of the USTs for upgrade by the addition of cathodic protection. These included: (a) soil resistivity measurements[1]; (b) soil type analysis; (c) moisture content; (d) presence of sulfides and chlorides; (e) soil pH; and (f) tank to electrolyte potentials. The external corrosion field testing at Hunter AAF was performed during the week of March 3, 1997.

3.4 DEMONSTRATION SITE/FACILITY BACKGROUND AND CHARACTERISTICS

The selection of demonstration sites for condition assessment of USTs was based on the following factors:

1. The USTs to be inspected needed to be empty, cleaned and to have been in service for at least 10 years. This ensured that some corrosion had taken place so that the USTs were representative of the older population of USTs to which 40 CFR 280-281 specifically refers.

2. The USTs to be inspected were representative of typical DoD applications. This involved factors such as capacity, fuel content (both highly refined fuels such as gasoline and less refined product such as diesel fuel), use, and soil side environment.

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[1] RCC and Bushman's study reverified the high soil resistivity at Hunter Army Airfield which was documented in a 1978 Corrosion Survey Report by the U.S. Army Facilities Engineering Support Agency.

3. The USTs to be inspected needed to have filler pipes that were accessible to a vehicle towing a trailer.

4. The USTs installations needed a source of 110 VAC 20 amp power available or, less preferably, a comparable portable generator present.

For validation purposes, a site with a number of USTs marked for removal was practical in the event that an alternative UST might be needed. USTs with excessive structural degradation or those that had previously been exposed internally to rain or ground water were excluded as not being representative of the intended use of the robotic system. Also, in the absence of safety certification, a clean, de-fueled, non-explosive environment was required for these demonstrations.

Figure 2. Photograph of Hunter Army Airfield Underground Storage Tanks

4.0 PERFORMANCE ASSESSMENT

4.1 GENERAL OBSERVATIONS

The robotic inspection system produced an electronic data file consisting of tank wall thickness measurements and the corresponding tank position coordinates. An inspection rate of 250 ft^2/hr was achieved.

The data were less than 100% complete as a result of variations in the ultrasonic coupling to the tank wall. Inadequate ultrasonic coupling resulted in signals that could not be automatically analyzed to determine wall thickness. However, inadequate measurements were easily identified during data analysis, and were compensated by over-sampling. Comparability, accuracy, and precision are additional measures of data quality that were considered extensively in the validation inspection performed at Fort Lee. For the Fort Stewart inspections, the sampling required by ASTM ES40-94 **[5]** was considered sufficiently representative. Data completeness was determined by dividing the total number of non-zero data entries in a robotic inspection data set by the total number of entries in that data set. Precision was measured by computing the standard deviation of 30 thickness measurements.

4.2 SELECTED VALIDATION RESULTS FROM FORT LEE

The *in-situ Fury* and *ex-situ* micrometer measurements are shown in Figures 3 through 5. Laboratory analyses of the three 5x5 grid pattern readings were performed in accordance with ASTM G46 **[8]**. In addition, MRI performed independent ultrasonic measurements on a different grid system in accordance with an EPA procedure for the field evaluation of USTs. The comparison of the measurements is given in Table 1. The external hand held ultrasonic measurements taken by MRI **[9]**, which were almost identical to those called for by NLPA 631**[4]**, were, when considered alone, inadequate to determine the tank's condition. In fact, no measurement indicating a remaining wall thickness less than 50% of the original value (nominal 0.375 in.) was found. *Fury*, however, found several locations with wall thickness below 0.15 in. (see Figure 6).

The quantity, accuracy and usefulness of data obtained from *Fury* inspections were superior to those of data obtained from manual inspection methods. One person working inside a UST must cope with restricted operating conditions and poor visibility, which result in difficulty in deciding where to sample, and in accurately locating the sampling points. It is also very time-consuming to obtain 15% coverage manually.

One of the main advantages of the *Fury* robotic system is its ability to rapidly collect data while the unit is in motion. Virtually all of the data from Fort Lee were taken during the last day of a week-long effort after a number of other validation tasks had been completed. Table 2 shows the results of a statistical analysis for the full data set as separated into tank wall and end caps (which typically have a larger initial wall thickness). The *Fury* data can be displayed in a number of ways. With position coordinates associated with each measurement, the positions of the thinnest measurements can be displayed. Figure 6 shows the four thinnest ranges of measurement for the curved tank wall (displayed as if viewed from above and opened to each side from a longitudinal top seam). A feature along a lower circumference approximately eight feet from the southern end cap is evident.

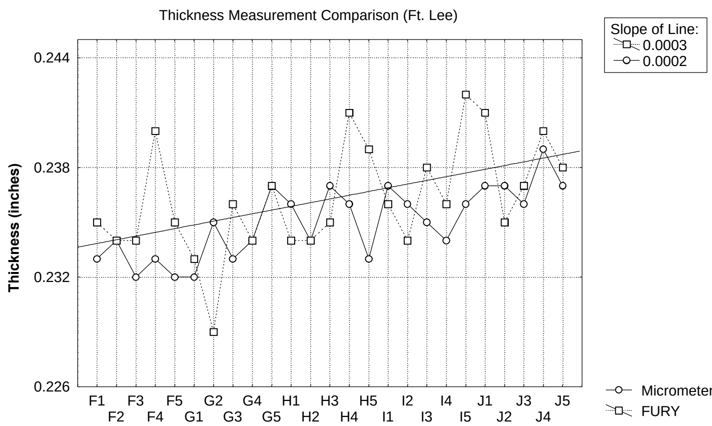

Figure 3. Mechanical vs. Fury Thickness Measurement (Bottom, Middle)

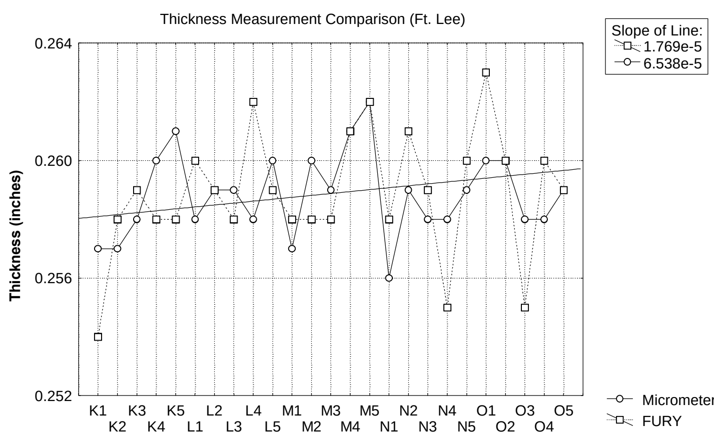

Figure 4. Mechanical vs. Fury Thickness Measurement (Bottom, Quarter)

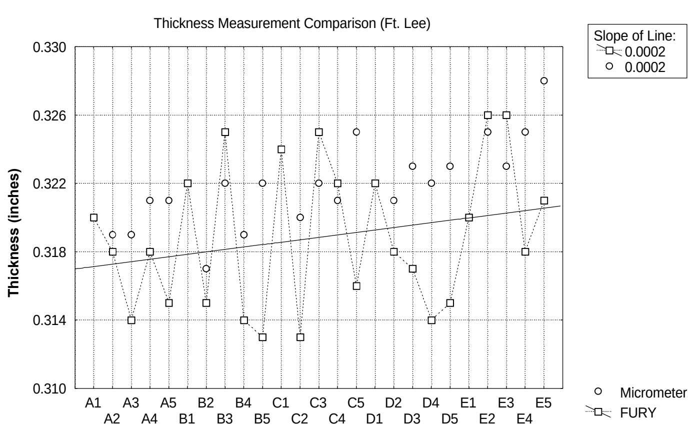

Figure 5. Mechanical vs. Fury Thickness Measurement (End Cap)

Table 1. Statistical Comparison of Fort Lee Thickness Data Sets

Method	Position	Valid n	Mean (in)	Min (in)	Max (in)	S. D. (in)
Fury Robot	Wall	111952	0.255	0.071	0.543	0.033
Micrometer	Wall	50	0.247	0.232	0.262	0.012
Hand-held Ultrasound*	Wall	77	0.245	0.222	0.274	0.012
Fury Robot	Far end cap	3683	0.324	0.251	0.485	0.0100
Fury Robot	Near end cap	18	0.234	0.071	0.441	0.124
Micrometer	End cap	20[#]	0.322	0.316	0.327	0.003
Hand-held Ultrasound*	North end cap	9	0.325	0.318	0.331	.005
Hand-held Ultrasound*	South end cap	9	0.322	0.312	0.328	0.006

*= MRI ultrasonic tank thickness measurements
# = five samples were rendered unusable by the cutting torch
n= number of data points
mean = average thickness of section
min = minimum thickness measured in section
max = maximum thickness measured in section
S.D. = standard deviation from the mean thickness

Table 2. Statistical Analysis of Complete Fort Lee Data Set

Position	Valid n	Mean (in)	Min (in)	Max (in)	S. D. (in)
Wall	111952	0.2549	0.0707	0.5426	0.0333
Far end cap	3683	0.3244	0.2508	0.4845	0.0100
Near end cap	18	0.2336	0.0707	0.4412	0.1243

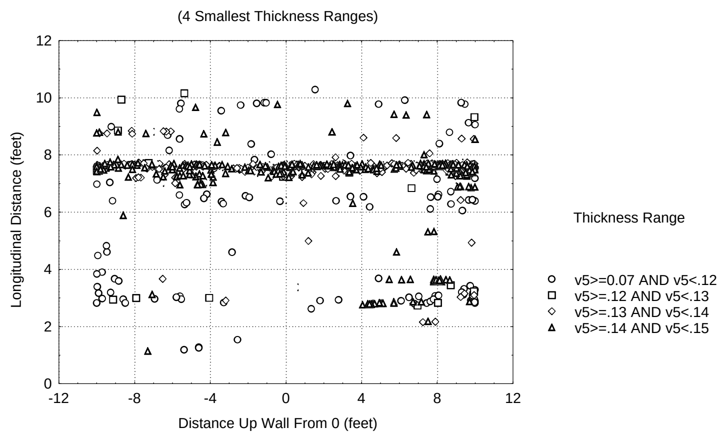

Figure 6. Location Distribution of 1,000 Thinnest Wall Thickness Measurements

This feature was visually confirmed after the tank was removed. One possible explanation is that during installation a lifting strap caused some initial damage which over time led to differential corrosive attack.

4.3 VALIDATION AND RESULTS AT HUNTER ARMY AIRFIELD

Fury collected in excess of 940,000 measurements from three USTs at Hunter Army Airfield. Acquiring the necessary data for each tank required less than 4 to 8 man-hours on-site time. Table 3 summarizes the results obtained after correction for an internal epoxy coating. The data were sorted according to thickness. Table 4 shows the results of an analysis of the 500 thinnest measurements (the so called "extreme values"). Histograms showing the number of measurements within successive ranges of wall thickness are shown in Figures 7 - 12. For each tank, these histograms show the overall distribution of thickness followed by a smaller region labeled C to show the data values at the thinnest end of the distribution. Tank 3 had approximately 71% of all data points between 0.345 and 0.395 in. For the smallest values approximately 0.04% of all data were between 0.070 and 0.100 in. Tank 4 had approximately 82% of all data points between 0.340 and 0.395 in. The smallest values for tank 4, ranging between 0.070 and 0.100 in., contained approximately 0.01% of all data points. Tank 5 data values fell mainly between 0.350 and 0.395 in., comprising 74% of all data points. The smallest values for this tank constituted approximately 1% of the data between 0.070 and 0.100 in. Tank 5 had the smallest values of all tanks with 0.35% of the total thicknesses residing at 0.070 in. The histogram for Region C for tank 5 (Figure 12) shows the exact number of data points for this thinnest region of the tank wall.

Table 3. Descriptive Analysis of Hunter Army Airfield Data Set

Tank	Valid n	mean (in)	min (in)	max (in)	std. dev. (in)
3	463408	0.38945	0.07096	0.56196	0.03232
4	321919	0.37601	0.07563	0.58053	0.03305
5	157183	0.36974	0.07034	0.57284	0.06551

Table 4. 500 Thinnest Data Points at Hunter Army Airfield

Tank	mean (in)	min (in)	max (in)	std. dev. (in)
3	0.12664	0.07096	0.14700	0.02270
4	0.13498	0.07563	0.14973	0.01299
5	0.07252	0.07034	0.07614	0.00164

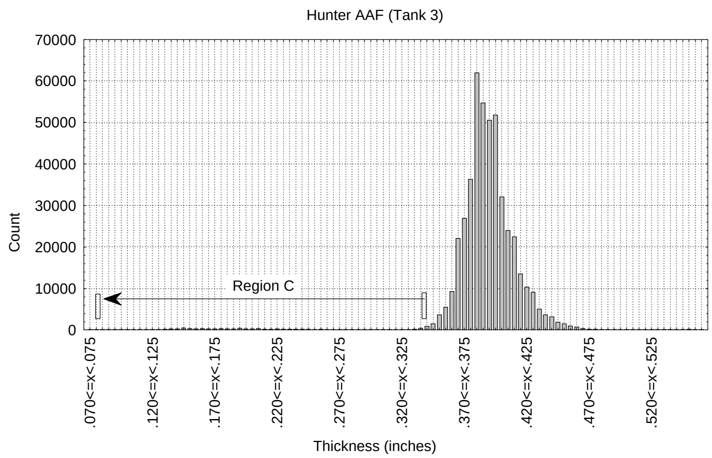

Figure 7. Tank 3 Thickness Distribution

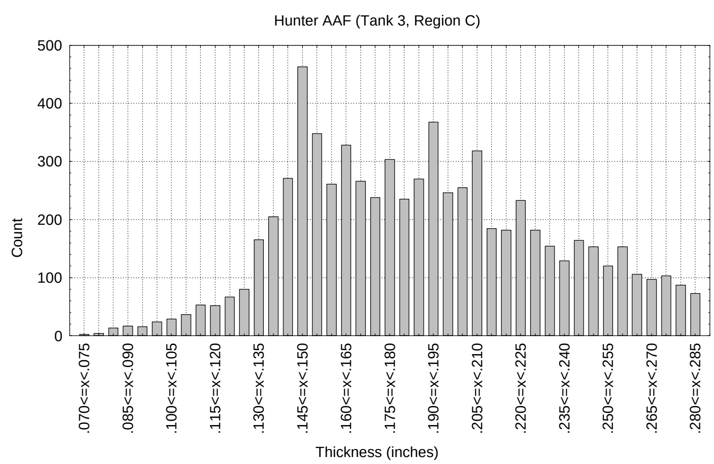

Figure 8. Thickness Distribution of Region C in Tank 3

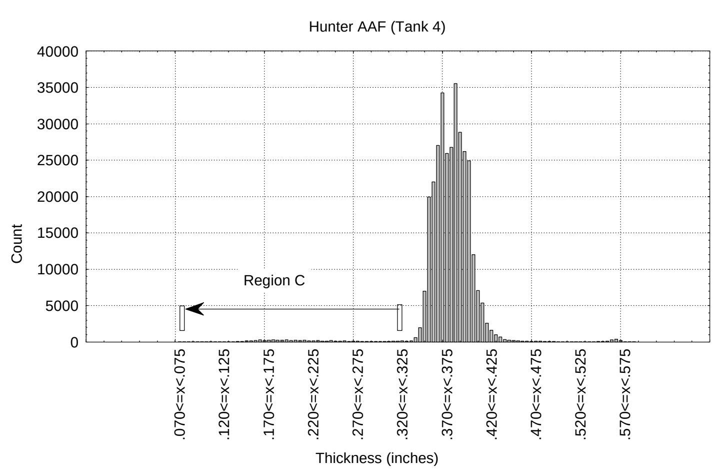

Figure 9. Tank 4 Thickness Distribution

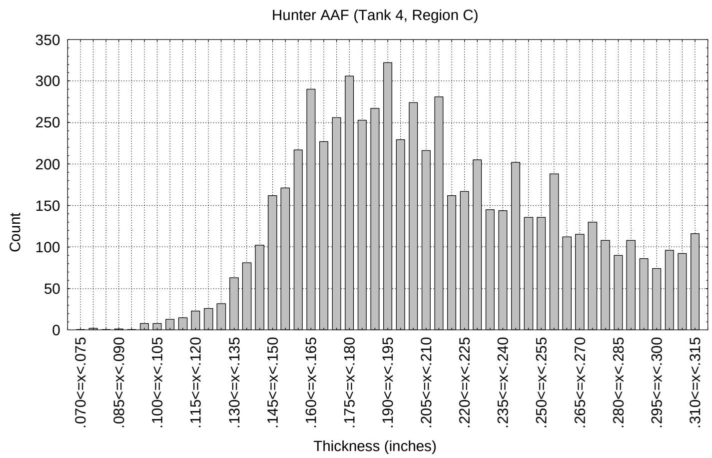

Figure 10. Thickness Distribution of Region C in Tank 4

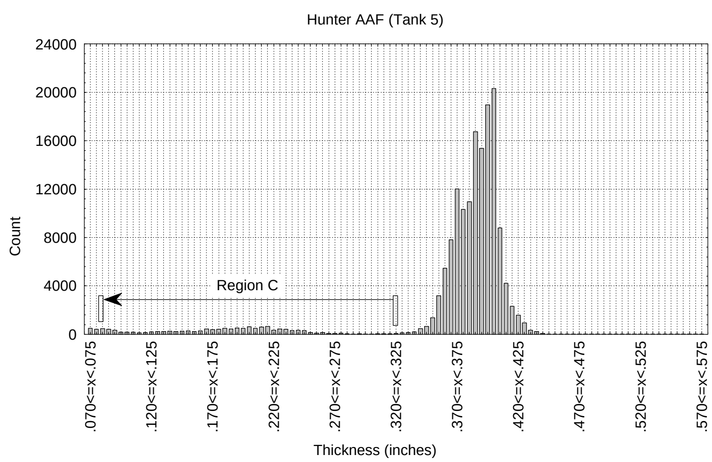

Figure 11. Tank 5 Thickness Distribution

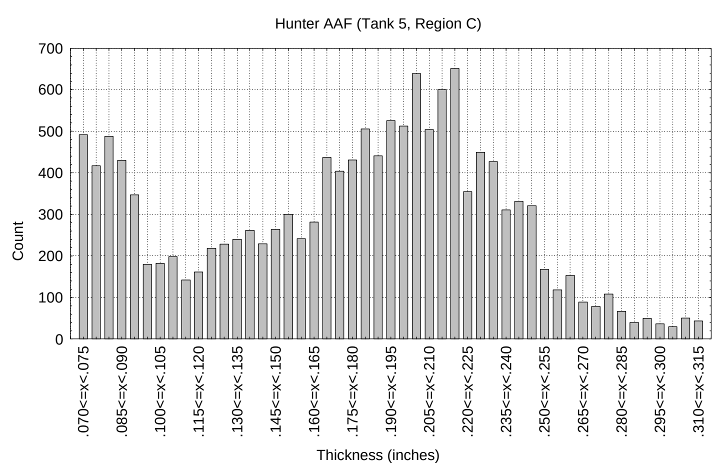

Figure 12. Thickness Distribution of Region C in Tank 5

4.4 STATISTICAL INTERPRETATION OF RESULTS

Descriptive and inferential statistics were considered for the large data sets obtained by *Fury* for each tank at Hunter AAF. Extreme value statistics were utilized on the maximum pit depths obtained from the data to determine probability of failure. Two approaches were employed assuming that maximum pit depths followed a Gumbel Type I distribution. The probability of rejecting this null hypothesis was determined. The scale and shape parameters of the distribution were estimated in an iterative manner.

First, graphical estimates were made by plotting the maximum pit depths on probability paper and employing least squares estimation. The resulting plots gave estimates for the slope and shape parameters, which were then used to calculate the probability of survival P_s of maximum pit depths. The graphical estimates were also used as initial estimates for Maximum Likelihood Estimates (MLE). Second, convergence based upon the Newton-Rhapson method for function minimization provided parameter estimates and confidence intervals for an MLE on the probabilities of occurrence of pit depths greater than the ones observed, which were compared with the graphical estimates for the probability of survival (a Gumbel Type III distribution).

4.5 SUITABILITY FOR CATHODIC PROTECTION UPGRADE

The external corrosion evaluation performed by RCC and Bushman yielded acceptable predicted lifetimes for all the USTs tested at Hunter AAF. Their report **[10]** concluded that the tanks were suitable for upgrading based on the external corrosion data gathered and the data evaluation equations ("MicroGPiper" Equation No. 6 and "Leakage Potential of USTs" Equation No. 6.) provided by CERL. While testing the sensitivity of the equations to deal with wide variations in soil characteristics, the second equation ("Leakage Potential of USTs") was found to more realistically model the probability of corrosion pitting penetration of USTs over the broadest potential range of variables.

The *Fury* inspection showed that Tanks 3 and 4 were in good shape while Tank 5 clearly showed a large number of observations at the lower thickness ranges. These observations combined with the findings from the external corrosion evaluation procedures, as required by ASTM ES40-94 **[5]**, indicated that tanks 3 and 4 were considered suitable for upgrade while tank 5 was not. From a corrosion engineering viewpoint, the character of the wall thickness histograms is intriguing. It may be that, as a tank undergoes the accumulated damage of corrosive degradation, the condition represented by Figures 8 and 10 evolves more toward a condition represented by Figure 12.

5.0 COST ASSESSMENT

An estimate of the potential life-cycle cost savings provided by a safety-certified *Fury* system is presented in Table 5. *Fury* system costs are compared to the cost of a conventional, manual UST inspection process, which involves de-fueling and cleaning the tank, confined-space human entry, and hand-held acoustic measurements. This cost assessment assumes purchase of a *Fury* unit by an Army installation. Alternatively, *Fury* inspection services could be purchased from a contractor on a per-tank basis.

At this stage of development, the accuracy of the cost estimate is +/- 30%, and a simple payback (with no discounting) is provided. A more accurate cost analysis could be made when *Fury* units are routinely manufactured, and increased experience with equipment operation and data analysis has been obtained

Cost Basis:

***Fury* System**	**Manual Inspection**
150 tanks inspected per year (250d/yr)	50 tanks inspected per year (250d/yr)
6 sites per year, 25 tanks per site	2 sites per year, 25 tanks per site
3 tanks inspected per week	1 tank inspected per week
No de-fueling necessary	De-fueling required
Some tank access (purging, cutting)	Tank access (purging, cutting, cleaning)
(15% of tanks have drop tubes)	(100% of tanks)
1 technician (100% time) @ $320/d	2 technician (100% time) @ $320/d
1 corrosion engineer (10% time) @$600/d	(NIOSH requires 2 men for confined space)
Site safety officer (2% time) @ $500/d	1 corrosion engineer (5% time) @$600/d
No per diem (local labor)	Site safety officer (2% time) @ $500/d
Electricity 0.5 kW (robot)	No per diem (local labor)
Inert gas purge 10 cylinders @ $100	Electricity 2 kW (fuel/sludge removal)
No hazwaste produced	Inert gas purge 5 cylinders @ $100
	Hazwaste disposal 5,000 gals @ $1/gal

Table 5. Cost Comparison of *Fury* vs. Manual Inspection

COST CATEGORY	*Fury* Remote Inspection System ($)	Conventional Manual Inspection ($)	Tank Excavation and Replacement ($)
Capital Costs			
Equipment Purchase	$75,000	$5,000	
Vehicle & Trailer	$25,000		
Total	$100,000	$5,000	
Annual O&M Costs			
Amortization (10-yr)	$10,000	$500	
On-site mobilization	$3,000	$1,000	
Maintenance	$5,000	$500	
Parts replacement	$10,000	$500	
Safety/equipment training	$2,000	$2,000	
Tank access	$2,500	$15,000	
Hazardous waste disposal	$0	$5,000	
Technician labor	$80,000	$160,000	
Corrosion engineer	$15,000	$7,500	
Safety officer	$2,500	$2,500	
Electricity	$100	$300	
Inert gas	$1,000	$500	
Demobilization (no hazwaste)	$3,000	$1,000	
Total Annual O&M Costs	$134,100	$196,300	
Cost per tank	$890	$3,930	
Cost per tank range (+/- 30%)	$600 - $1,200	$2,750 - $5,100	$30,000 - $300,000
Annual O&M Costs savings range (+ /-30%)	$43,500 - $80,900		
Savings per tank	$2,100 - $3,900		
SIMPLE PAYBACK PERIOD	< 2.5 years		

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

Using *Fury* for condition assessment would result in estimated cost savings of $2,100-$3,900 per tank when compared to conventional manual inspection. Tank owners could either purchase a robotic system or procure inspection services under contract.

Removal of hazardous tank contents, followed by tank excavation and replacement is an expensive effort. The full replacement of 30 tanks at Hunter AAF was estimated at $10-12 million by an architectural/engineering contractor. Therefore, a significant cost would be avoided for all existing USTs found suitable for upgrade. Thus, the results of *Fury* condition assessments can be used to make better informed management decisions concerning tank upgrade versus replacement. The potential nationwide cost savings could be as high as $10 billion if the replacement of only 10% of the UST inventory could be avoided. A comprehensive study performed by the United States Environmental Protection Agency (EPA) estimated there are 796,000 motor fuel storage tanks within the United States with a mean age of 12 years **[11]**.

6.2 PERFORMANCE OBSERVATIONS

The *Fury* remote robotic inspection and condition assessment system was both validated and demonstrated at two separate sites on a total of four tanks. Virtually all of the capabilities of the system were verified and documented. In terms of wall thickness data acquisition, *Fury* accurately determines a tank's current condition, and advances the state-of-the-art by three or four orders of magnitude compared to current methods. Another benefit is the ability to inspect a tank without the need for human entry. *Fury* may also be used for ongoing, periodic assessment of cathodically protected tanks because corrosion is a dynamic process that would continue if cathodic protection were not working effectively.

6.3 REGULATORY AND OTHER ISSUES

Fury will allow UST owners to more cost-effectively comply with federal, state and local requirements imposed by the 1998 deadline of 40 CFR 280-281, and to satisfy the official DoD requirement N 2.III.2.a Environmentally Safe Storage Capability. Safety certification for submerged operation in fueled tanks would greatly promote regulatory acceptance, and this is being actively sought. Producing a fully sealed robot suitable for immersion service is a top priority. In future inspections in fully fueled tanks, the tether handling system would limit any fuel spills associated with tether removal. Release of volatile organic compounds (VOCs) would be prevented by the use of an inert gas in the tank head-space.

6.4 OTHER SIGNIFICANT OBSERVATIONS

Even though the 1998 deadline has passed, there remains a need for UST condition assessment. To meet the 1998 upgrade requirements, many UST owners temporarily closed their tank systems. EPA estimates that as of February 1999, 73,000 tanks were temporarily closed. Temporary closure of substandard systems may not exceed 12 months unless the implementing agency grants an extension **[12]**. AEC temporarily removed some of its USTs from service to meet 1998 compliance deadline. The US Army Training and Indoctrination Command (TRADOC) has 400 USTs that require inspection.

Although compliance with the 1998 deadline is thought to be approximately 80% and increasing, EPA still needs to ensure that all owners comply with the technical requirements and that UST systems are operated and maintained properly. EPA will work to help states evaluate the effectiveness of UST systems — especially with leak detection, cathodic protection and tank lining — to ascertain that they operate properly and to identify ways in which these systems can be improved **[12]**. Ongoing condition assessment is likely to be an issue. Also, inspection of aboveground tanks every 5 years is mandated by American Petroleum Institute Regulation API-653.

Possible alternate uses of the robotic inspection system are to obtain wall thickness information on a variety of steel structures including ship hulls, oil platforms, submersed sheet piling, locks and dams, and nuclear applications. The ability of *Fury* to operate below liquid level would provide additional flexibility. Investigation of *Fury* inspection of submerged sheet piling already has been studied in the Cuyahoga River in Cleveland, OH **[13]**.

Installation of other sensors in the inspection assembly in place of the ultrasonic transducer would allow other types of inspections to be performed. Possible sensors include magnetic flux, far field eddy current, electromagnetic acoustic transducer (EMAT) and corrosion rate measurement. Re-approval of the assembly would then be required to operate the robotic inspection system with a new sensor in classified areas.

The *Fury* project won a Department of the Army Research and Development Achievement Award for 1998 and a detailed patent has been submitted to the Corps of Engineers Headquarters (case number 486). In addition, a Cooperative Research and Development Agreement (CRADA) is being sought with an industry partner to investigate other applications.

6.5 LESSONS LEARNED

Some weaknesses in the functional reliability of *Fury* were apparent during the demonstrations. Aqueous couplant managed to short out some of the on-board electronics on the second day of testing at Fort Lee, which necessitated a day of repairs. Mechanical weaknesses were also identified in rotator pins and a universal joint used in the main drive. However, no problem identified was insurmountable and thus far all problems were able to be addressed in the field.

The operator of the *Fury* system must be sure to turn on the data storage system and to maintain the data files at a reasonable size in order to aid later processing. Developing computer spreadsheets to facilitate the data analysis required considerable time. RCC and Bushman recommended that CERL should consider refining and protecting computer models to facilitate the data input while providing a uniform and rapid means of data assessment. This would not eliminate the need for a corrosion expert but would greatly reduce the time required to reach a valid conclusion about the suitability of a UST system for upgrade.

6.6 SCALE-UP

There are no scale-up issues. The *Fury* prototype was tested in the configuration intended for future production. It performed in-field UST condition assessment at an acceptably fast rate. Future manufactured units would be of identical design, with minor design improvements incorporated as part of normal system evolution and as operational experience increases.

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APPENDIX A

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